Long Term Stability Monitoring of Aqua MODIS Thermal Emissive Bands through Radiative Transfer Modeling

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ABSTRACT

Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua has been in operation providing continuous global observations for science research and applications since 2002. The long term stability of thermal emissive bands (TEBs) of Aqua MODIS was monitored through inter-comparison with measurements by hyperspectral infrared sensors such as AIRS on Aqua and IASI on MetOp satellite or through long term vicarious monitoring over cold targets such as Dome-C and deep convective clouds (DCC). In this paper, a radiative transfer modeling-based simulation model using Community Radiative Transfer Model (CRTM) is developed to perform long term monitoring of the stability of TEBs of Aqua MODIS. CRTM is a fast-radiative transfer model for calculations of radiances for satellite infrared radiometers and is able to output infrared radiance and brightness temperature at spectral bands of MODIS. Long term European Centre for Medium-Range Weather Forecasts (ECMWF) global atmospheric reanalysis data such as temperature and humidity profiles are used as inputs to the CRTM simulation. By confining the area of interest to be over low to middle latitude ocean, the long-term stabilities of selected Aqua MODIS TEBs are monitored through O-B brightness temperature (BT) bias between MODIS measurements and BT retrieval from CRTM simulation. The consistency and relative stability between Aqua MODIS and ECMWF reanalysis data for surface channels of MODIS are evaluated. In addition, the radiative transfer modeling with CRTM also enables us to evaluate the impacts of long term variation of global CO_2 distribution on the O-B BT biases for CO_2 channels of Aqua MODIS through comparison of simulations with constant or long term variable CO_2 as inputs. The O-B analysis with RTM show that Aqua MODIS surface channels are all radiometrically stable with yearly BT bias drift less than 0.004K/year for B20, B22, B23 and ~0.01K/year for B31 and B32. The CO_2 absorption channels of Aqua MODIS, e.g. B33-B36, are stable with BT bias drift < 0.005K/year.

Keywords: MODIS, RTM, CRTM, TEB calibration, O-B Bias

1. INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) is currently in operation onboard the Earth Observing System Aqua spacecraft launched on May 4, 2002[1–6]. MODIS is a scanning radiometer-based imager and has thirty-six spectral bands. Among 36 bands, channels 1–19 and 26 with wavelengths from 0.41 μm to 2.2 μm are the reflective solar bands (RSBs), and channels 20–25 and 27–36 with wavelengths from 3.7 μm to 14.5 μm are the thermal emissive bands (TEBs). MODIS TEBs are calibrated on-orbit on a scan-by-scan basis using a blackbody at a fixed scan-angle.

Previous studies track the long term stability of Aqua MODIS TEBs through inter-comparisons with co-located measurements by hyperspectral infrared sensors such as Atmospheric Infrared Sounder (AIRS) on Aqua and Infrared Atmospheric Sounding Interferometer (IASI) on MetOp satellite[7], or with SNPP NOAA-20 VIIRS after correcting the spectral response function (SRF) difference using Cross-track Infrared Sounder (CrIS) on SNPP or NOAA-20[8,9]. These inter-comparison studies can only cover limited number MODIS channels due to either finite spectral coverages of hyperspectral sounder or limited matching bands between MODIS and VIIRS. Alternatively, cold invariant vicarious sites such as DOME-C[10] or stable Deep Convective Cloud (DCC)[11,12] have also been monitored to track long term stability of Aqua and Terra MODIS TEBs. The brightness temperature of these cold targets is typically outside the MODIS blackbody calibration range. In Díaz *et al.*[13], in-situ sea surface temperature (SST) measurements were used to provide useful references for MODIS over more characteristic higher scene temperatures. Such comparisons with in situ measurements cover mostly the MODIS surface channels and need to account for the transmission through the atmosphere in the analysis.

In this paper, radiative transfer modeling (RTM) based simulation model using Community Radiative Transfer Model (CRTM) is developed to monitor long term radiometric stability of Aqua MODIS TEBs. The European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA) global atmosphere data are used as inputs to the simulation. The RTM-based simulation can cover all bands of interest and is a first principle physics-based scene simulation. The simulated top of atmosphere (TOA) brightness temperature (BT) data from CRTM using ECMWF data as inputs for MODIS channels are referred as the background BT from modeling. The bias between observed BT and simulated BT is called Observation–Background (O-B) bias. Long term trending of mean O-B biases for MODIS TEBs provides an alternative independent validation of MODIS TEBs stability.

In the following sections, we first introduce the methodology of RTM modeling for Aqua MODIS stability monitoring. In Section 3, the consistency and relative stability between Aqua MODIS and ECMWF reanalysis data for surface and CO_2 absorption channels of MODIS are evaluated with long term O-B BT bias derived from CRTM simulation. In addition, we performed impact analysis of global carbon dioxide concentration growth on BT variation of Aqua MODIS CO_2 absorption channels through comparison of long-term O-B biases from simulations with fixed and time-varying CO_2 profiles as inputs.

2. METHODOLOGY

2.1 MODIS TEBs and RTM simulation model setup

Figure 1 shows the spectral response functions of 16 MODIS TEBs overlaid onto the spectral transmittance of various gas types. In this paper, the radiometric stability monitoring of MODIS TEBs is focused on the surface channels B20, B22, B23, B31 and B32 of Aqua MODIS and CO_2 absorption channels B33-B36 of MODIS (See Figure 1). The stability of other MODIS TEBs such as B24-B30 that are affected by various gas absorptions (Figure 1) and will be investigated in another study.

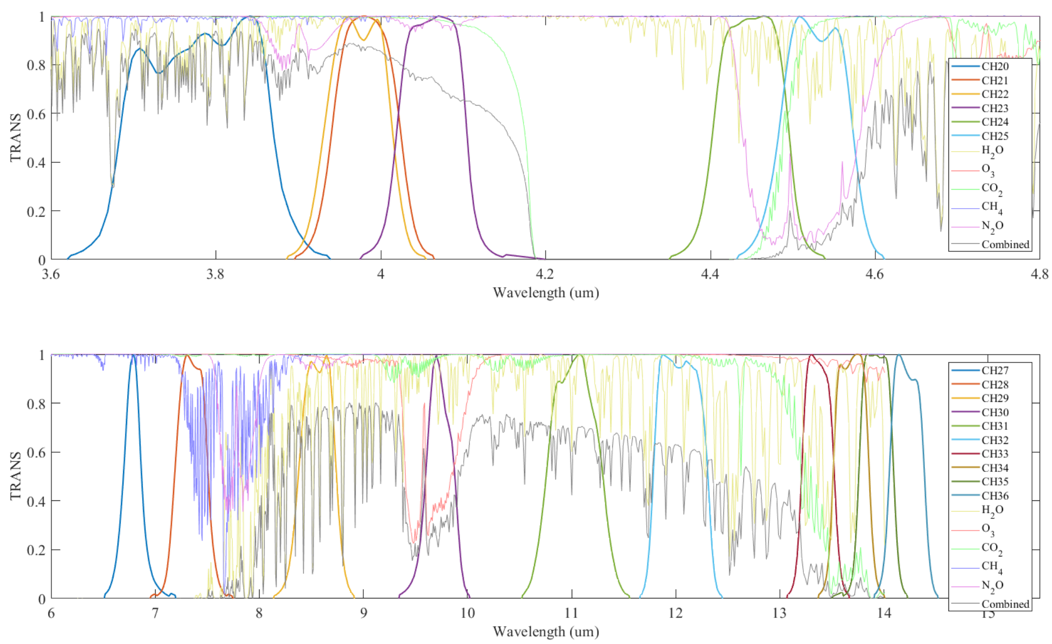

Figure 1. Aqua MODIS SRFs overlaid with spectral transmittances of various gas types.

Figure 2 shows the RTM simulation setup with CRTM as the simulator for long term O-B bias evaluation of MODIS TEBs. CRTM is a fast-radiative transfer model for calculations of Top of Atmosphere (ToA) radiances for space-born infrared or microwave radiometers and is able to output infrared/microwave radiance and temperature at IR/MW sensors' spectral resolutions. CRTM is physics-based radiative transfer modeling. Simulation coefficients for Aqua MODIS TEBs were first trained with Line-by-Line Radiative Transfer Model (LBLRTM) and then fed into CRTM. In this study, the CO_2 and ozone atmospheric absorption effects are included in coefficient set.

The RTM simulations were carried out with time-varying surface data and atmospheric profile data from ECMWF as inputs. ECMWF Re-Analysis (ERA) global atmospheric and climate reanalysis dataset are from 4DVAR data assimilation

which uses a fixed version of a numerical weather prediction (NWP) system (IFS-CY31r2) to produce the reanalyzed data. The NWP system blends or assimilates observations with a previous forecast to obtain the best fit to both. The results of this blending serve as the starting point for the next forecast. The fixed version in ERA dataset ensures that no spurious trends are caused by an evolving NWP system since the changing observing system can create such trends.

Long term ECMWF global atmospheric reanalysis data such as temperature and water vapor profiles, and CO_2 and ozone profiles are used as inputs to the CRTM simulation. Surface parameters including skin temperature, wind speed and wind direction are obtained from ECMWF's ERA-Interim reanalysis model which is based on 6 hourly increments. The data from ECMWF were collected with 0.75° spatially gridded resolution which is equivalent to a spatial resolution of ~80 km at equator. Ozone, water vapor, and temperature profiles from ECMWF are coordinated at 37 mandatory pressure levels and are available from ground to up to ~0.1 hPa. Carbon dioxide profiles from ECMWF are recorded at 60 pressure levels.

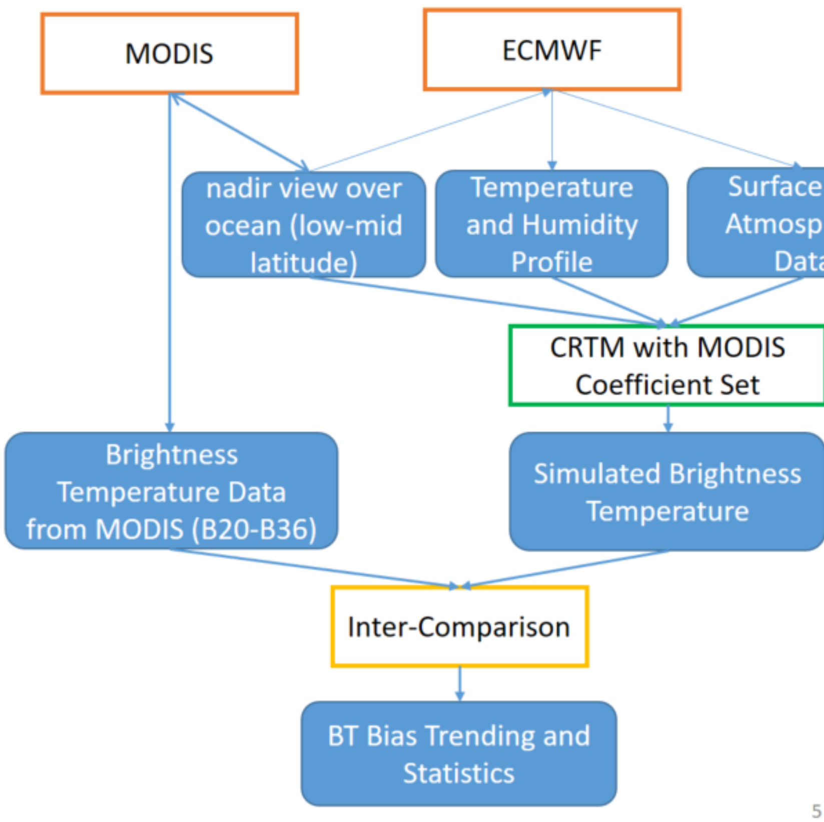

Figure 2. RTM simulation setup with CRTM as the simulator for long term O-B bias evaluation of MODIS TEBs.

As shown in Figure 2, in the RTM simulation, Aqua MODIS orbital nadir locations over oceans and corresponding times are collected and fed to process the global ECMWF data. Spatial and temporal interpolations of ECMWF surface and profile parameters are performed to derive the input parameters for CRTM. Simulated TOA BT data from CRTM over Aqua MODIS nadir are compared with corresponding MODIS measurements (MODIS Standard Collection 6.1) for O-B BT bias evaluation.

2.2 Scene target selection and long-term O-B trending

The evaluation of MODIS TEB stability is carried out through comparison of Aqua MODIS measurements with the RTM-modeled BT data using the atmosphere and surface reanalysis data from ECWMF, i.e. O-B analysis. In this study, Aqua MODIS nadir view data are collected and the areas of interest (AOIs) are confined to be over low to mid-latitude (-60 to 60 degrees in latitude) ocean which are warm temperature targets. Areas with solar zenith angles between 80 and 100 degrees are excluded to avoid the terminator region. Both MODIS and ECMWF data on the 15th day of each month from 2003 to 2018 are collected. The ending year in 2018 for the O-B analysis is due to the availability of ECMWF data.

For each O-B BT bias comparison, about 100 data points around the center of the target location at satellite nadir are collected. To remove measurements due to scene non-uniformity, only scenes with standard deviation of BT < 0.5 K are

kept for all MODIS TEBs analyzed. The AOIs with cloud contaminations are screened out with 3 sigma filtering using MODIS surface channel B20 data. After the uniformity and cloud contamination screening, the number of remaining valid pixels for O-B comparison are about 30,000 each day, which solidifies the statistical advantages of the RTM-based stability analysis. The ensemble of O-B BT biases over valid scenes during each day of interest are combined to derive characteristic monthly O-B BT bias (mean) and its uncertainty (standard deviation) for each MODIS TEB analyzed. The monthly time series of O-B BT biases over 16 years are further analyzed to evaluate the long-term radiometric stability of MODIS TEBs of interest.

3. TRENDING OF AQUA MODIS TEBS RADIOMETRIC STABILITY WITH RTM

3.1 Long term stability monitoring of Aqua MODIS surface TEB channels from O-B analysis

The first set of Aqua MODIS TEBs to be evaluated for long term stability monitoring are surface channels of MODIS, e.g. B20-B23, B31, and B32. Figure 3 shows the long term (16-year) trending of O-B (ECMWF model) BT bias for selected TEBs of Aqua MODIS along with their uncertainties. In general, the O-B analysis with RTM shows that surface temperature channels (B20-B23, B31, and B32) of Aqua MODIS are quite stable and consistent with ECMWF reanalysis data. The long-term time series of O-B BT biases are further trended with linear regression to derive the yearly BT drift rate for each MODIS TEB which are listed in Table 1. This enables quantitative evaluation of the stability of MODIS TEBs. The residual absolute O-B bias between MOIDS observation and CRTM simulation results can be due to the setup of RTM. The RTM simulation is better suited for sensor trending/stability analysis than absolute bias evaluation. It can be seen that Aqua MODIS surface channels B20 to B23 are all radiometrically stable with the yearly BT bias drift less than 0.004 K/year. For B31 and B32 of Aqua MODIS, the yearly BT bias drift is around 0.01 K/year.

In the TEB bias and stability analysis through inter-comparison between MODIS and AIRS[7], B20 of Aqua MODIS was completely excluded from the analysis because the spectral overlap between two instruments was insufficient. Our analysis shows that B20 of Aqua MODIS is quite stable. MODIS B21 and B22 have very similar SRFs and the same center wavelength. Our analysis shows that MODIS B21 is stable, but with much larger O-B BT bias fluctuations (< 1.5 K) than MODIS B22. This is due to that MODIS B21 is specifically designed for fire detection and its quality assurance (QA) for non-fire scenes is very low[4]. Our analysis shows that Aqua MODIS B22 is more reliable than B21 for typical Earth surface temperatures.

Radiometric stabilities of surface channels B31 and B32 of Aqua MODIS after 2012 were extensively monitored through inter-comparison with NPP VIIRS matching channels in Li et al.[8,9]. Our long-term O-B BT bias analysis shows that the surface channels B31 and B32 of Aqua MODIS maintains their stabilities with yearly BT bias drift around 0.01 K/year over all 16 years. In Shrestha and Xiong[10] and Chang *et al.*[11], the stability of MODIS surface TEBs were validated with long term measurements over clod targets such as DOME-C and deep convective clouds. Our analysis independently validates the stability of these MODIS surface channels over scenes with more characteristic higher temperatures.

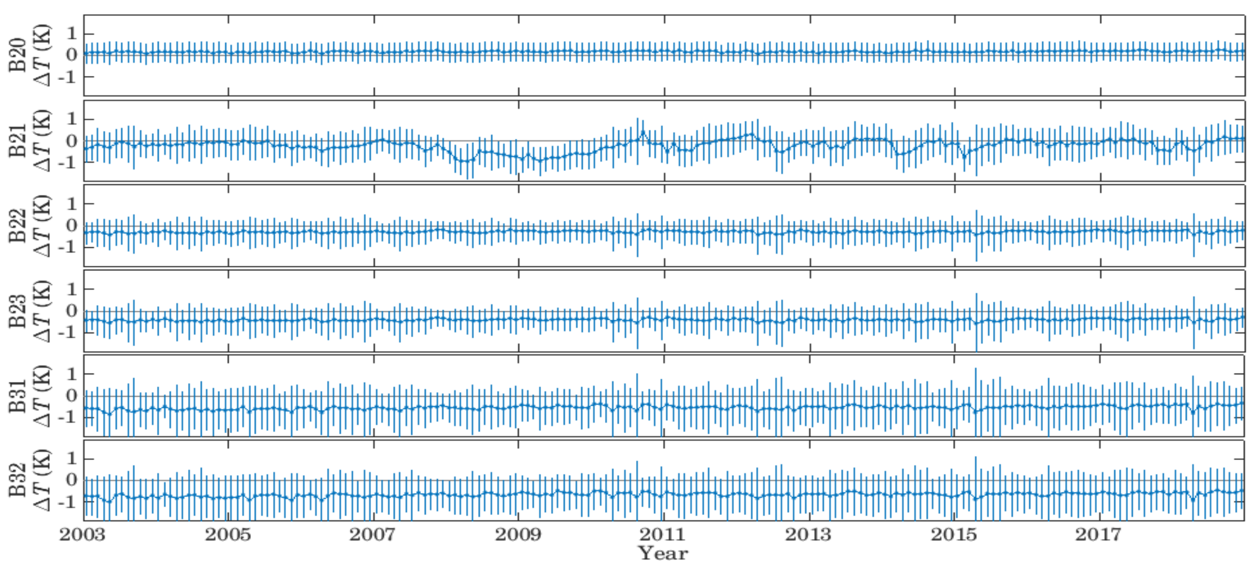

Figure 3. Long term trending of O-B (ECMWF model) BT bias for surface channels of Aqua MODIS, e.g. B20-B23, B31 and B32, along with their uncertainties over 16 years.

Table 1. Yearly BT drift (K/year) of Aqua MODIS surface TEBs, e.g. B20-B23, B31 and B32, derived from O-B analysis with CRTM simulation.

Channel	Wavelength (μm)	Slope (K/year)
B20	3.750	0.0027
B21	3.959	0.0120
B22	3.959	0.0029
B23	4.050	0.0036
B31	11.03	0.0105
B32	12.02	0.0107

3.2 Evaluation of long-term Aqua MODIS CO2 channel stability and impacts of global CO2 concentration growth with RTM

The B33-B36 channels of Aqua MODIS are infrared sounding channels and are largely affected by the carbon dioxide (CO_2) absorption as the thermal radiation transmitting through the atmosphere. During the lifetime of Aqua MODIS, global carbon concentration continues to increase (Figure 4). The CRTM simulation has the flexibility of using either fixed initial CO2 profile or time-varying CO2 profiles collected from ECMWF as the simulation input. By comparing the long-term O-B bias from simulations with fixed and time-varying global CO_2 profiles (Figure 5), the stability of and impacts of global CO_2 concentration growth on Aqua MODIS B33-B36 are quantified.

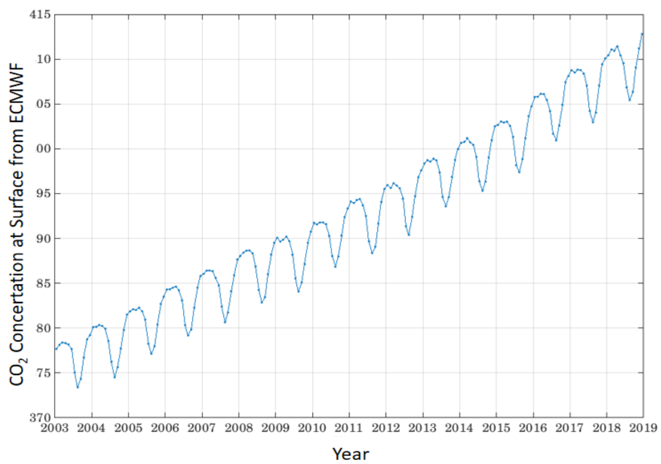

Figure 4. Global CO2 concentration growth at surface from ECMWF.

Figure 5 shows that after accounting for the growth of global CO_2 concentration, the long-term O-B BT bias variations (red curves) of Aqua MODIS B33-B36 are shown to be very stable. More quantitatively, Table 2 shows the yearly O-B BT bias drift (K/year) of MODIS CO_2 channels derived from the linear regression fitting of time series of O-B BT bias data shown in Figure 5. The yearly BT bias drift of Aqua MODIS CO_2 absorption channels, e.g. B33-B36, are all less than 0.005K/year.

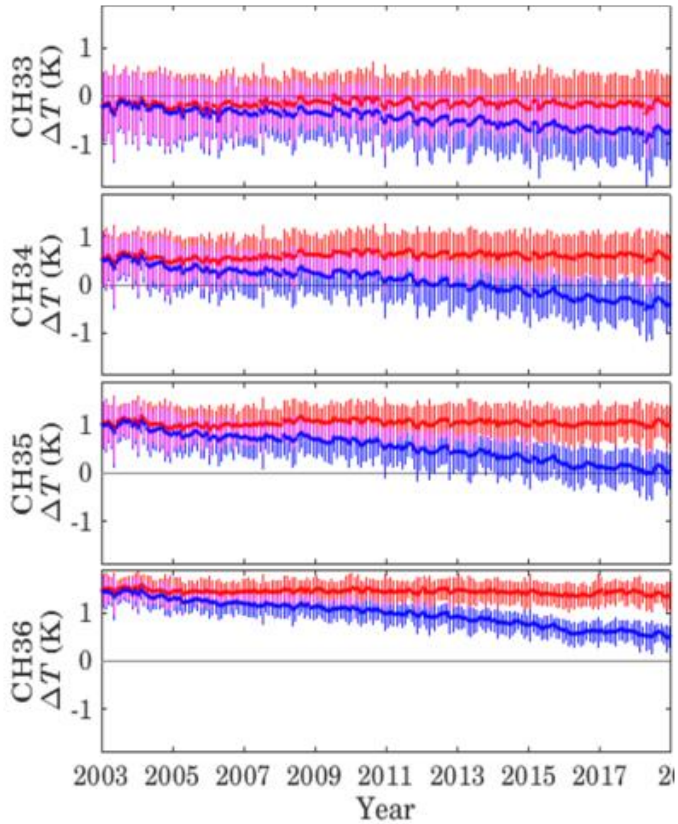

Figure 5. Comparison of long-term O-B BT bias (K) variation and uncertainties derived from inter-comparison with CRTM simulations with fixed (blue) and time varying (red) CO2 profiles for B33-B36 of Aqua MODIS.

Table 2. Yearly O-B BT bias drift (K/year) of MODIS CO2 channels derived from inter-comparison with CRTM simulations with fixed and time-varying CO2 profiles as inputs and ending BT difference between two inter-comparisons.

MODIS Bands	**Wavelength (μm)**	**Slope with Fixed CO_2 Profile (K/year)**	**Slope with Time Varying CO_2 Profile (K/year)**	**Ending ΔT (K) between Two Simulations**
B33	13.335	-0.0352	0.0005	0.58
B34	13.635	-0.0574	0.0039	0.99
B35	13.935	-0.0599	0.0008	0.97
B36	14.245	-0.0568	-0.0049	0.86

The well-calibrated infrared detectors of MODIS maintain long term stability as shown in Figure 5 and Table 2. Long term MODIS CO_2 channel data also provide the opportunity to reveal the impacts of global CO_2 concentration growth on the variation of global mean BT of these CO_2 channels. Figure 5 shows the time series of O-B BT bias (blue curves in Figure 5) between Aqua MODIS measurements and CRTM simulation with fixed initial CO_2 profiles as input. There are long term decreasing trends in O-B BT bias for CRTM simulation with fixed CO_2 profiles in comparison with the results (red curves in Figure 5) derived from simulation with time-varying ECMWF reanalysis data. The difference between O-B BT bias time series (red vs. blue curves in Figure 5) from two inter-comparisons shows the global mean BT increases in these infrared channels due to the long-term growth of global CO_2 concentration. Table 2 also listed the ending difference between O-B BT biases of simulations with fixed and time-varying CO_2 profiles. The impacts of CO_2 growth over 16 years on BT increase of these Aqua MODIS TEBs are more significant in B34 to B36 (0.86 to 0.99 K) than B33 (0.58 K) since the CO_2 absorption coefficient is smaller for B33 than the other three channels. Combining the well-calibrated MODIS TEB measurements with RTM simulation help quantify the long-term impact of global carbon dioxide concentration growth on the BT increase in MODIS CO_2 absorption channels.

4. SUMMARY

In this paper, an RTM-based sensor radiometric stability monitoring model has been developed. The model is based on O-B BT bias analysis through inter-comparison of BT measurements by infrared sensors with the CRTM-modeled BT using the atmosphere and surface reanalysis data from ECMWF. Long term ECMWF global atmospheric reanalysis data such as temperature, humidity, CO_2 and ozone profiles, and surface temperature and wind data are used as inputs to the CRTM simulation. The O-B bias analysis scheme was applied to perform long term radiometric stability monitoring of Aqua MODIS TEBs. The focuses of radiometric stability evaluation in this paper are on Aqua MODIS surface channels B20-B23, B31, and B32, and CO2 absorption channels B33-B36. Since ECMWF data has global coverage and are continuous in time and CRTM has comprehensive spectral coverage, the O-B bias analysis is not limited by spatial and temporal availability of global atmosphere data or spectral coverage of reference sensors. There are about 30,000 MODIS measurements daily that can be used for O-B analysis after applying the uniformity and cloud contamination filtering, which can significantly reduce the uncertainty in the O-B BT bias calculation.

The O-B analysis with RTM show that Aqua MODIS surface channels B20-B23, B31 and B32 are all radiometrically stable with yearly BT bias drift less or around 0.01K/year. The CO_2 channels of Aqua MODIS, e.g. B33-B36, are stable with yearly BT bias drift < 0.005K/year. The well-calibrated Aqua MODIS CO_2 TEB channels maintain sustained long-term stability and enable the evaluation of the impacts of global carbon dioxide concentration growth on the trending of global mean BT for these channels. Through comparison of O-B BT bias from simulations with fixed or variable CO_2 profiles as inputs, the long term impact of global carbon dioxide concentration growth on the global mean BT increase are shown to be around 0.58 to 1 K over 16 years from 2003 to 2018 for Aqua MODIS B33 to B36 channels.

The ECMWF global atmospheric and climate reanalysis dataset are derived from 4DVAR data assimilation which assimilates observations with a previous forecast to obtain the best fit to both. Such inter-comparison of MODIS TEB measurements with global reanalysis data through RTM provides validation of radiometric stability of Aqua MODIS TEBs with Weather Forecasting model and other space-borne and ground-based observations.

ACKNOWLEDGEMENT

Dr. Tung-Chang Liu's work was supported by the NASA grant (NNX17AE79A).

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